

Can Stop be Light Enough for TRISTAN ? *

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Abstract

We examine a possibility for existence of a light supersymmetric partner of the top quark (stop) with mass 15~16GeV in the framework of the minimal supergravity GUT model. Such light stop could explain the slight excess of the high p_T cross section of the $D^{*\pm}$ -meson production in two-photon process at TRISTAN. We point out that the existence of such stop could change the dominant decay mode of the gluino and could weaken present experimental bound on the mass of gluino. It seems that there is a finite parameter region allowing existence of the light stop even if we consider the present experimental data. Inversely, if the light stop was discovered at TRISTAN, masses and mixing parameters of the other SUSY partners as well as masses of the Higgs and the top will be severely constrained, for example, $m_{\tilde{g}} \simeq 85\text{GeV}$, $m_{\tilde{W}_1} \lesssim 50\text{GeV}$, $110\text{GeV} \lesssim m_{\tilde{\ell}} \lesssim 140\text{GeV}$, $120\text{GeV} \lesssim m_{\tilde{q}} \lesssim 160\text{GeV}$, $\theta_t \simeq 0.9$, $m_h \lesssim 65\text{GeV}$ and $130\text{GeV} \lesssim m_t \lesssim 140\text{GeV}$. We also discuss briefly the proton decay and the dark matter constraints.

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1 Introduction

A possibility for discovery of a light supersymmetric partner of the top quark (stop) with mass $15 \sim 16$ GeV (*TRISTAN stop*) from analyses of the high p_T $D^{*\pm}$ -meson production in two-photon process is one of important topic at this Workshop [1]. Needless to say, the discovery of the stop will bring us a great physical impact. It will be the first signature of the supersymmetry as well as the top flavor. In particular, I heard that the discovery of the top flavor is the endless-dream of TRISTAN. The disagreement between the measured value and the standard model prediction now becomes 3σ level [1], which should be compared to 1.5σ reported previously [2].

It is natural to ask, "Have not already been such light stop and neutralino excluded by LEP or Tevatron experiments?" and "Could such light stop be favored theoretically?" In this paper we examine the possibility for existence of the light stop and the neutralino in the minimal supergravity GUT (MSGUT) scenario [3, 4] taking into account of the present experimental bounds on the SUSY parameter space. While some parts of our results have been reported in the previous paper [5], I will present some new results in this talk.

2 Light stop : its theoretical bases

In the framework of the MSSM [6], the stop mass matrix in the $(\tilde{t}_L, \tilde{t}_R)$ basis is expressed by

$$\mathcal{M}_t^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 & a_t m_t \\ a_t m_t & m_{\tilde{t}_R}^2 \end{pmatrix}, \quad (1)$$

where m_t reads the top mass. The SUSY mass parameters $m_{\tilde{t}_{L,R}}$ and a_t are parametrized in the following way [7] :

$$m_{\tilde{t}_L}^2 = \tilde{m}_{Q_3}^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) + m_t^2, \quad (2)$$

$$m_{\tilde{t}_R}^2 = \tilde{m}_{U_3}^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2 \theta_W + m_t^2, \quad (3)$$

$$a_t = A_t + \mu \cot \beta, \quad (4)$$

where $\tan \beta$, μ and A_t denote the ratio of two Higgs vacuum expectation values ($= v_2/v_1$), the SUSY Higgs mass parameter and the trilinear coupling constant, respectively. The soft breaking masses of third generation doublet \tilde{m}_{Q_3} and the up-type singlet \tilde{m}_{U_3} squarks are related to those of first (and second) generation squarks as

$$\tilde{m}_{Q_3}^2 = \tilde{m}_{Q_1}^2 - I, \quad (5)$$

$$\tilde{m}_{U_3}^2 = \tilde{m}_{U_1}^2 - 2I, \quad (6)$$

where I is a function proportional to the top quark Yukawa coupling α_t and is determined by the renormalization group equations in the MSGUT. Throughout of this paper we adopt the notation in Ref.[8].

There are two origins for lightness of the stop compared to the other squarks and sleptons, i) smallness of the diagonal soft masses $m_{\tilde{t}_L}^2$ and $m_{\tilde{t}_R}^2$ and ii) the left-right stop

mixing. Both effects are originated from the large Yukawa interaction of the top. The origin i) can be easily seen from Eqs.(2)~(6). The diagonal mass parameters $m_{\tilde{t}_L}^2$ and $m_{\tilde{t}_R}^2$ in Eq.(1) have possibly small values owing to the negative large contributions of I proportional to α_t in Eqs.(5) and (6). It should be noted that this contribution is also important in the radiative $SU(2) \times U(1)$ breaking in the MSGUT. The Higgs mass squared has similar expression to Eqs.(5) and (6) ;

$$\tilde{m}_{H_2}^2 = \tilde{m}_{L_1}^2 - 3I, \quad (7)$$

where $\tilde{m}_{L_1}^2$ denotes the soft breaking mass of first generation doublet slepton. The large contribution of I enables $\tilde{m}_{H_2}^2$ to become negative at appropriate weak energy scale. In order to see another origin ii) we should diagonalize the mass matrix Eq.(1). The mass eigenvalues are obtained by

$$m_{\tilde{t}_1, \tilde{t}_2}^2 = \frac{1}{2} \left[m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 \mp \left((m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + (2a_t m_t)^2 \right)^{1/2} \right]. \quad (8)$$

and the corresponding mass eigenstates are expressed by

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \tilde{t}_L \cos \theta_t - \tilde{t}_R \sin \theta_t \\ \tilde{t}_L \sin \theta_t + \tilde{t}_R \cos \theta_t \end{pmatrix}, \quad (9)$$

where θ_t denotes the mixing angle of stops :

$$\tan \theta_t = \frac{a_t m_t}{m_{\tilde{t}_R}^2 - m_{\tilde{t}_L}^2}. \quad (10)$$

We see that if SUSY mass parameters and the top mass are the same order of magnitude, small $m_{\tilde{t}_1}$ is possible owing to the cancellation in the expression Eq. (8) [10, 9].

After the mass diagonalization we can obtain the interaction Lagrangian in terms of the mass eigenstate \tilde{t}_1 . We note, in particular, that the stop coupling to the Z -boson ($\tilde{t}_1 \tilde{t}_1^* Z$) depends sensitively on the mixing angle θ_t . More specifically, it is proportional to

$$C_{\tilde{t}_1} \equiv \frac{2}{3} \sin^2 \theta_W - \frac{1}{2} \cos^2 \theta_t. \quad (11)$$

Note that for a special value of $\theta_t \sim 0.98$, the Z -boson coupling completely vanishes [11].

3 Present bounds on stop mass

Before discussion of experimental bounds on the stop mass $m_{\tilde{t}_1}$, we examine the decay modes of the stop. In the MSSM, the stop lighter than the other squarks and gluino can decay into the various final states : $\tilde{t}_1 \rightarrow t \tilde{Z}_1$ (a), $b \tilde{W}_1$ (b), $b \ell \tilde{\nu}$ (c), $b \nu \tilde{\ell}$ (d), $b W \tilde{Z}_1$ (e), $b f f' \tilde{Z}_1$ (f), $c \tilde{Z}_1$ (g), where \tilde{Z}_1 , \tilde{W}_1 , $\tilde{\nu}$ and $\tilde{\ell}$, respectively, denote the lightest neutralino, the lighter chargino, the sneutrino and the charged slepton. If we consider the light stop with mass lighter than 20 GeV, the first five decay modes (a) to (e) are kinematically forbidden due to the model independent lower mass bounds for respective particles ; $m_t \gtrsim 90 \text{ GeV}$, $m_{\tilde{W}_1} \gtrsim 45 \text{ GeV}$, $m_{\tilde{\ell}} \gtrsim 45 \text{ GeV}$ and $m_{\tilde{\nu}} \gtrsim 40 \text{ GeV}$. So there left (f) and (g). Hikasa

and Kobayashi [10] have shown that the one-loop mode $\tilde{t}_1 \rightarrow c\tilde{Z}_1$ (g) dominates over the four-body mode $\tilde{t}_1 \rightarrow bff'\tilde{Z}_1$ (f). It is absolutely true in the case considered here, because the mode (f) is negligible by the kinematical suppression, $m_{\tilde{t}_1} \sim m_{\tilde{Z}_1} + m_b$. So we can conclude that such light stop will decay into the charm quark jet plus the missing momentum taken away by the neutralino with almost 100% branching ratio. Note that the width of stop in this case is very small, i.e., the order of magnitude of eV.

Naively, it will be expected that Tevatron and/or LEP can set severe bounds on the stop mass through the processes ; $gg \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow c\bar{c}\tilde{Z}_1\tilde{Z}_1$ (Tevatron) and/or $Z \rightarrow \tilde{t}_1\tilde{t}_1^*$ (LEP). However, the situation is not so obvious. Baer et al. [12] have performed the analyses of the experimental data of 4pb^{-1} integrated luminosity Tevatron running, and have obtained the results that the stop could easily be escaped the detection if $m_{\tilde{Z}_1} \gtrsim 10\text{GeV}$. Such large neutralino mass could make the charm quark jets softer. Consequently the stop production cross section plotted against the missing transverse energy becomes smaller than the present upper bounds, where they impose cuts on the missing transverse energy. Moreover, we should point out that LEP cannot exclude the light stop for appropriate mixing angle θ_t . In Fig.1, we show the excluded region in $(\theta_t, m_{\tilde{t}_1})$ plane by LEP in terms of $\Delta\Gamma_Z < 28\text{MeV}$ (95% C.L.), where we included the QCD correction in the calculation [11]. We find that there is no bound on the stop mass if the mixing angle θ_t is larger than about 0.7. The origin of such sensitivity of $\Gamma(Z \rightarrow \tilde{t}_1\tilde{t}_1^*)$ is in the fact that the $\tilde{t}_1\tilde{t}_1^*Z$ coupling is proportional to $C_{\tilde{t}_1}$ (11) [11]. TRISTAN have ever settled the lower mass bounds on squarks $m_{\tilde{q}} \gtrsim 25\text{GeV}$ assuming massless photino in terms of the direct search $e^+e^- \rightarrow \tilde{q}\tilde{q}^*$ [13]. Those bounds, however, are invalidated if $m_{\tilde{q}} - m_{\tilde{Z}_1} < 8\text{GeV}$. In addition, the mass bound $m_{\tilde{t}_1} \gtrsim 37\text{GeV}$ from the direct stop search by DELPHI group at LEP is valid only for $m_{\tilde{t}_1} - m_{\tilde{Z}_1} > 17\text{GeV}$ [14]. Recent analyses of the direct search at VENUS group [15] show that the *TRISTAN stop* ($m_{\tilde{t}_1} = 15 \sim 16\text{GeV}$ and $m_{\tilde{Z}_1} = 13 \sim 14\text{GeV}$) just confronts the experimental bounds. In fact it seems that such stop has been excluded for $m_{\tilde{t}_1} - m_{\tilde{Z}_1} > 3\text{GeV}$. Recently Okada [16] has investigated possible bounds on masses of the stop and the neutralino from the experimental data of the $b \rightarrow s\gamma$ decay. He has shown that the light stop with mass $m_{\tilde{t}_1} \lesssim 20\text{GeV}$ has not been excluded by the data. After all, we can conclude that there is no bound on the stop mass for $m_{\tilde{Z}_1} \gtrsim 10\text{GeV}$ and $\theta_t \gtrsim 0.7$ if $m_{\tilde{t}_1} - m_{\tilde{Z}_1} < 3\text{GeV}$.

4 Present bounds on gaugino parameters

In the MSSM, masses and mixing parameters of the gaugino-higgsino sector are determined by three parameters μ , $\tan\beta$ and M_2 , where M_2 denotes the soft breaking SU(2) gaugino mass. Some regions in $(\mu, \tan\beta, M_2)$ parameter space have already excluded by the negative searches for the SUSY particles at some collider experiments. First, we concern the experimental data at LEP ; i) lower bound on the mass of lighter chargino, $m_{\tilde{W}_1} \gtrsim 45\text{GeV}$, ii) upper bound on the branching ratio of the visible neutralino modes of the Z , $\text{BR}(Z \rightarrow \text{vis.}) \equiv \sum_{i,j} \Gamma(Z \rightarrow \tilde{Z}_i\tilde{Z}_j)/\Gamma_Z^{\text{tot}} < 5 \times 10^{-5}$ [17], and iii) upper bound on the invisible width of the Z , $\Gamma(Z \rightarrow \tilde{Z}_1\tilde{Z}_1) < 16.2\text{MeV}$ [18]. In Fig.2 we show the region excluded by the experimental data i) \sim iii) in (μ, M_2) plane for $\tan\beta=2$. We also plot a contour of $m_{\tilde{Z}_1} = 13 \sim 14\text{GeV}$ which can explain the TRISTAN data as mentioned above.

First we realize that the neutralino with mass $13 \sim 14\text{GeV}$ can be allowed in the range $-180\text{GeV} \lesssim \mu \lesssim -110\text{GeV}$ for $\tan\beta=2$. Note that the contour of $m_{\tilde{Z}_1} = 13 \sim 14\text{GeV}$ lies in the excluded region for $\mu > 0$. If we take larger (smaller) values of $\tan\beta$, the allowed region becomes narrower (wider). We find that the allowed region disappears for $\tan\beta \gtrsim 2.4$. Second we see that $m_{\tilde{Z}_1} = 13 \sim 14\text{GeV}$ corresponds to $M_2 = 22 \sim 24\text{GeV}$ in the allowed region and we can find that this correspondence is independent on the values of $\tan\beta$. Consequently, we can take $M_2 = 22 \sim 24\text{GeV}$ as an input value in the following calculation. Allowed region in $(\mu, \tan\beta)$ plane fixed by $M_2 = 24\text{GeV}$ is shown in Fig.3. Additional bounds on the $(\mu, \tan\beta)$ parameter space from the negative search for the neutral Higgs boson at LEP will be discussed bellow. It is worth mentioning that the lightest neutralino \tilde{Z}_1 is almost photino $\tilde{\gamma}$ in the allowed parameter range in Fig.3. In fact, the photino component of the neutralino is larger than 98% in the range.

Next we should discuss bounds on the gaugino parameters from the hadron collider experiments. If we assume *the GUT relation*,

$$m_{\tilde{g}} = M_3 = \frac{\alpha_s}{\alpha} \sin^2 \theta_W M_2 \quad (12)$$

in the MSGUT, the gluino mass $m_{\tilde{g}}$ bounds from the hadron colliders could be converted into the bounds on M_2 [19]. Naively accepted gluino mass bound at CDF is

$$m_{\tilde{g}} \gtrsim 150\text{GeV} \quad (90\%\text{C.L.}), \quad (13)$$

which can be easily converted into the bound on M_2 by Eq.(12) as $M_2 \gtrsim 42\text{GeV}$, which rejects the above fixed value, $M_2 = 22 \sim 24\text{GeV}$. (Note that *the GUT relation* (12) depends sensitively on $\sin^2 \theta_W$ and α_s . Here we take $\sin^2 \theta_W = 0.230$ and $\alpha_s = 0.12$.) Fortunately, however, the bound (13) is not realistic. To get realistic bound we must include the cascade decay in the analyses [20]. The gluino mass bound at CDF taken into account of the cascade decays $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_{2,3,4}$ and $\tilde{g} \rightarrow u\bar{d}\tilde{W}_{1,2}$ as well as the direct decay $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1$ has reported as [21]

$$m_{\tilde{g}} \gtrsim 95\text{GeV} \quad (90\%\text{C.L.}) \quad (14)$$

for $\mu = -250\text{GeV}$ and $\tan\beta = 2$, for example. Here we must include, moreover, the additional decay mode, $\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1^* \tilde{Z}_1$, which becomes another seed for the cascade decay because the stop and neutralino could be light enough from TRISTAN data. In Fig.4 we show the $m_{\tilde{g}}$ dependence of the branching ratio of gluino, where we include the mode $\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1^* \tilde{Z}_1$ and sum up quark flavors $q, q' = u, d, c, s$. We take $\tan\beta = 2$, $\mu = -150\text{GeV}$, $m_{\tilde{t}_1} = 15\text{GeV}$, $\theta_t = 0.7$, $m_t = 135\text{GeV}$ and $M_2 = 22\text{GeV}$, and take $m_{\tilde{g}}$ as a free parameter. The squark masses are taken as $m_{\tilde{q}} = 2m_{\tilde{g}}$, where $m_{\tilde{q}} \equiv m_{\tilde{u}_{L,R}} = m_{\tilde{d}_{L,R}} = m_{\tilde{c}_{L,R}} = m_{\tilde{s}_{L,R}}$. The branching ratio of the direct decay mode $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1$, which is important in the \tilde{g} search in terms of large \cancel{E}_T signature, is reduced substantially as $\text{BR}(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1) \lesssim 50\%$, even for the light gluino with mass $m_{\tilde{g}} \gtrsim 60\text{GeV}$. Therefore, we should reconsider the UA2 bound $m_{\tilde{g}} \gtrsim 79\text{GeV}$ [22] obtained under the assumption $\text{BR}(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1) \sim 100\%$ as well as the CDF bound (14). For the value $m_{\tilde{g}} = 85\text{GeV}$ determined by *the GUT relation*, $\text{BR}(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1) \sim 10\%$, which should be compared with $\text{BR}(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1) \sim 70\%$ obtained when there is no stop mode. We try to simulate the Monte-Carlo calculation in order to get the gluino mass bounds from the CDF gluino searches. In Fig.5 we show the

expected number of events in 4.3pb^{-1} integrated luminosity Tevatron running. In this calculation, we take kinematical selection cuts presented at the CDF paper [20]. We find that the gluino with mass $80\sim 90\text{GeV}$, which is predicted by the *TRISTAN stop* events, just confronts the experimental bound.

While all squark masses are independent parameters in the MSSM, they are determined by small numbers of input parameters in the MSGUT. Hereafter we adopt *the GUT relation* and will reconsider the Tevatron bound after presenting the results of the MSGUT analyses. Note that if we remove *the GUT relation*, the gluino can be heavy with no relation with M_2 and $m_{\tilde{Z}_1}$ and $\text{BR}(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1)$ can be small.

5 MSGUT analysis

Before presenting our results for the analysis, we will summarize briefly the calculational scheme in the MSGUT [8]. In this scheme the independent parameters, besides the gauge and Yukawa couplings, at GUT scale M_X are the SUSY Higgs mass parameter $\mu(M_X) = \mu_\infty$ and three soft breaking mass parameters : the common scalar mass $\tilde{m}_{\tilde{f}}^2(M_X) = \tilde{m}_{\tilde{H}_i}^2(M_X) = m_\infty^2$, the common gaugino mass $M_3(M_X) = M_2(M_X) = M_1(M_X) = M_\infty$ and the trilinear coupling $A_\tau(M_X) = A_b(M_X) = A_t(M_X) = \dots = A_\infty$. As usual, we take the Higgs mixing parameter B as $B(M_X) = A_\infty - m_\infty$. All the physical parameters go from M_X down to low energies governed by the renormalization group equations (RGE) [4]. In the following we neglect all Yukawa couplings except for the top. This is not a bad approximation as long as $\tan\beta$ is not too large ($\ll m_t/m_b$), which is the case we consider here, $\tan\beta \lesssim 2.4$.

As for the evolution of the gauge couplings $\alpha_i(t)$ and the gaugino masses $M_i(t)$, we take the input values $\alpha^{-1}(m_Z) = 128.8$ and $\sin^2\theta_W = 0.230$. Assuming the SUSY scale is not too different from m_Z , we may use the SUSY beta function at all scales above m_Z for simplification. Then one finds $M_X = 3.3 \times 10^{16}\text{GeV}$, $\alpha_\infty^{-1} (= \alpha_3^{-1}(M_X) = \alpha_2^{-1}(M_X) = \alpha_1^{-1}(M_X)) = 24.3$ and $\alpha_3(m_Z) = 0.12$. Moreover, the RGE for gaugino masses are easily solved as

$$M_i(t) = \alpha_i(t) \frac{M_\infty}{\alpha_\infty}. \quad (15)$$

After solving the all other RGE for the physical parameters, all physics at weak scale m_Z are determined by the six parameters $(m_\infty, A_\infty, M_\infty, \mu, \tan\beta, m_t)$. There are, moreover, two conditions imposed on the parameters to have the correct scale of $\text{SU}(2) \times \text{U}(1)$ breaking. So we can reduce the number of the independent parameters to four out of the six. Here we take the four independent input parameters as $(M_\infty, \mu, \tan\beta, m_t)$. As we have discussed earlier, furthermore, we can fix one of input value, $M_2 = 24\text{GeV}$, which corresponds to $M_\infty = 29.3\text{GeV}$ for $\sin^2\theta_W = 0.230$ (see Eq.(15)). After all, there remain the only three parameters $(\mu, \tan\beta, m_t)$.

We seek numerically solutions to give the light stop with mass $m_{\tilde{t}_1} = 16\text{GeV}$ varying the three parameters $(\mu, \tan\beta, m_t)$. The results are shown in Fig.6, which is same parameter space in Fig.3. Each line corresponds to contour of $m_{\tilde{t}_1} = 16\text{GeV}$ for the fixed m_t value. We also plot the mass m_h contours of the lighter CP-even neutral Higgs boson as well as the LEP bounds from the data discussed above. First we realize that

there is rather narrow but finite range allowing existence of the light stop, if the top was slightly light too, $m_t \lesssim 140\text{GeV}$. Second we find that the light stop solutions give inevitably the light Higgs boson, $m_h \lesssim 60\text{GeV}$. While we have included the radiative correction in the calculation of the Higgs mass [23], deviations δm_h from the tree level results are not so large, $|\delta m_h| \lesssim 2\text{GeV}$. The neutral Higgs is standard Higgs like, i.e., $\sin(\beta - \alpha) \simeq 1$, where α denotes the Higgs mixing angle [24]. A result from the negative searches for the MSSM Higgs at LEP could set another constraint on the SUSY parameter space in Fig.6. The present limit on the MSSM (SM like) Higgs mass is

$$m_h \gtrsim 60\text{GeV} \quad (95\%\text{C.L.}) \quad (16)$$

for $\sin(\beta - \alpha) \simeq 1$ [25]. Note, however, that this is obtained based upon the assumption that the Higgs do not decay into the stop. Here we must consider the fact that the neutral Higgs could have dominant decay mode $h \rightarrow \tilde{t}_1 \tilde{t}_1^*$ with almost 100% branching ratio if the stop were light enough. In this case energies of visible jets from the Higgs production would become softer and it can be smaller than the detection lower cuts. Therefore, if we incorporate such decay mode in data analyses, the present lower bounds will be expected to be weakened. We try to simulate the Monte-Carlo calculation in order to get the Higgs mass bounds from the LEP Higgs searches. In Fig.7 we show the expected number of events in 39pb^{-1} integrated luminosity LEP running. In this calculation, we take kinematical selection cuts presented at the DELPHI paper [26]. While the number of events of the neutrino channel $Z \rightarrow hZ^* \rightarrow h(\nu\bar{\nu})$ reduced considerably, the reduction rates of the events in the lepton channel $Z \rightarrow hZ^* \rightarrow h(\ell^+\ell^-)$ are not so large. This is because the selection cuts on the visible jet energies are not so essential in the lepton channel. From Fig.7(c) we find the present lower bound on the Higgs mass is about 55GeV . Adopting the bound $m_h \gtrsim 55\text{GeV}$, we can choose four typical parameter sets (A), (B), (C) and (D), denoted in Fig.8. Input and output values of the parameters of the sets (A), (B), (C) and (D) are presented in Table I. The set (D) [(C)] has the largest [smallest] values of the scalar fermion masses, the stop mixing angle and the top mass and has the smallest [largest] value of the lighter chargino mass. The set (A) [(C)] gives the largest [smallest] neutral Higgs mass. The set (B) corresponds to the almost center point in the allowed range. We find that masses and mixing parameters are severely constrained, for example, $m_{\tilde{W}_1} \lesssim 50\text{GeV}$, $110\text{GeV} \lesssim m_{\tilde{\ell}} \lesssim 140\text{GeV}$, $120\text{GeV} \lesssim m_{\tilde{q}} \lesssim 160\text{GeV}$ and $\theta_t \simeq 0.9$.

6 Phenomenological implications

Now we are in position to discuss some consequence of the light stop scenario in the MSGUT and give strategies to confirm or reject such possibility in the present and future experiments. Some numerical results are calculated with the typical parameter sets (A), (B), (C) and (D) in Table I.

The existence of the light stop with mass $15 \sim 16\text{GeV}$ will alter completely decay patterns of some ordinary and SUSY particles (sparticles). First we discuss the top decay [12, 27]. In our scenario, the top can decay into final states including the stop; $t \rightarrow \tilde{t}_1 \tilde{Z}_1$, $\tilde{t}_1 \tilde{Z}_2$ and $\tilde{t}_1 \tilde{g}$. Branching ratios of the top for the typical parameter sets are presented in Table II. We find that the gluino mode $t \rightarrow \tilde{t}_1 \tilde{g}$ has about 40% branching ratio and competes with the standard mode $t \rightarrow bW^+ \sim 50\%$. Strategies for the top search at

Tevatron would be forced to change because the leptonic branching ratios of the top would be reduced by the dominance of the stop-gluino mode.

Decay patterns of the Higgs particles will be changed too. The lighter CP-even neutral Higgs decays dominantly into the stop pair, $h \rightarrow \tilde{t}_1 \tilde{t}_1^*$, owing to the large Yukawa coupling of the top. In rough estimation, we obtain

$$\text{BR}(h \rightarrow \tilde{t}_1 \tilde{t}_1^*) \simeq \frac{1}{1 + \frac{3m_b^2 m_h^2}{2m_t^4}} \simeq 1. \quad (17)$$

This fact would change the experimental methods of the Higgs searches at the present and future collider experiments. More detail analyses of the charged [28] and neutral Higgs bosons are presented separately.

Now we discuss briefly the light stop impact on the sparticle decays. The lightest charged sparticle except for the stop is the lighter chargino \tilde{W}_1 . The two body stop mode $\tilde{W}_1 \rightarrow b\tilde{t}_1$ would dominate over the conventional three body mode $\tilde{W}_1 \rightarrow f\bar{f}'\tilde{Z}_1$. As a consequence, it would be difficult to use the leptonic signature in the chargino search at e^+e^- and hadron colliders. Since the chargino \tilde{W}_1 , the neutral Higgs h and the gluino \tilde{g} , whose dominant decay modes are respectively $\tilde{W}_1 \rightarrow b\tilde{t}_1$, $h \rightarrow \tilde{t}_1 \tilde{t}_1^*$ and $\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1^* \tilde{Z}_1$, are copiously produced in the other sparticle decays, many stops would be expected in the final states of the sparticle production. For example, $\tilde{\ell}_L \rightarrow \nu \tilde{W}_1 \rightarrow \nu(b\tilde{t}_1)$, $\tilde{q}_{L,R} \rightarrow q\tilde{g} \rightarrow q(\tilde{t}_1 \tilde{t}_1^* \tilde{Z}_1)$, $\tilde{q}_L \rightarrow q'\tilde{W}_1 \rightarrow q'(b\tilde{t}_1)$ and $\tilde{Z}_{i(i \neq 1)} \rightarrow \tilde{Z}_1 h \rightarrow \tilde{Z}_1(\tilde{t}_1 \tilde{t}_1^*)$. Note that the dominant decay modes of the right-handed sleptons would be unchanged, i.e., $\text{BR}(\tilde{\ell}_R \rightarrow \ell \tilde{Z}_1) \simeq 100\%$.

Needless to say, all experimental groups, AMY, TOPAZ and VENUS, at TRISTAN should perform a detail data analyses to confirm or reject the exciting scenario. Furthermore, we can see that the stop and its relatively light accompaniments, the gluino \tilde{g} , light neutralinos $\tilde{Z}_{1,2}$, and neutral Higgs h , should be visible at LEP, SLC, HERA and Tevatron. Especially, LEP could search allowed region presented in Figs.1 and 8 in terms of the width of Z -boson and the direct stop search. First we find from Table I, the stop mixing angle θ_t is severely limited as $\theta_t \simeq 0.9$ in the allowed range in Fig.8. It is interesting that $\theta_t \simeq 0.9$ is not *input* but *output* of the MSGUT calculation. As the stop search in terms of $\Delta\Gamma_Z$ would be difficult in this case, the direct search for $e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1^*$ will be important [14]. Second, the whole allowed region in Fig.8 can be explored by the precise measurement of $\text{BR}(Z \rightarrow \text{vis.})$. In fact, the smallest value of the neutralino contribution $\sum_{i=j \neq 1}^{i,j} \Gamma(Z \rightarrow \tilde{Z}_i \tilde{Z}_j) / \Gamma_Z^{\text{tot}}$ to $\text{BR}(Z \rightarrow \text{vis.})$ is about 2×10^{-5} (see Table III). Of course, the Higgs h search at LEP with the stop signature $h \rightarrow \tilde{t}_1 \tilde{t}_1^*$ is very important to set further constraint on the allowed region. In this case searches for the lepton channel $Z \rightarrow hZ^* \rightarrow h(\ell^+ \ell^-)$ would be more important than the neutrino channel. Clearly, the lighter chargino, $m_{\tilde{W}_1} \lesssim 50\text{GeV}$, would be visible at LEP II.

As mentioned before, Tevatron will play a crucial role in confirming or rejecting the light stop scenario in the MSGUT with *the GUT relation*. In this case the existence of relatively light gluino, $m_{\tilde{g}} \simeq 85\text{GeV}$, with substantially large decay fraction $\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1^* \tilde{Z}_1$ is one of definite prediction. Values of branching ratios of the gluino for the typical parameter sets (A), (B), (C) and (D) are tabulated in Table IV. The branching ratio of direct decay mode $\text{BR}(\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1) = 22 \sim 34\%$ is expected in the allowed range. These values are

rather large compared to those in Fig.4. This is originated from the fact that allowed mass values of squarks except for the heavier stop \tilde{t}_2 are relatively small $m_{\tilde{q}} \lesssim 160\text{GeV}$. In the gluino search at Tevatron the mixed signature, $p\bar{p} \rightarrow \tilde{g}\tilde{g}X \rightarrow (\tilde{t}_1\tilde{t}_1^*\tilde{Z}_1)(q\bar{q}\tilde{Z}_1)X$, and in turn the two-jets events would be dominant signature. Squarks could be within reach of Tevatron too. Signatures of the squarks, however, would be unusual because of their cascade decays such as $\tilde{q}_{L,R} \rightarrow q\tilde{g} \rightarrow q(\tilde{t}_1\tilde{t}_1^*\tilde{Z}_1)$ and $\tilde{q}_L \rightarrow q'\tilde{W}_1 \rightarrow q'(b\tilde{t}_1)$. Note again that the light stop and neutralino can survive even after the negative search for the gluino and squarks at Tevatron if we remove *the GUT relation* Eq.(12). Removal of *the GUT relation* corresponds to the change of boundary conditions on the soft gaugino masses at the unification scale M_X . Owing to this change the RGE solution for the stop mass is modified and in turn we will get different allowed parameter region from Fig.8. The analyses based on such models will be presented elsewhere.

The ep collider HERA could search the light stop through its pair production process $ep \rightarrow e\tilde{t}_1\tilde{t}_1^*X$ via boson-gluon fusion [29]. The total cross section of the process is larger than about 10pb for $m_{\tilde{t}_1} \lesssim 20\text{GeV}$, which is independent on the mixing angle θ_t . That is, $\sigma \gtrsim 10\text{pb}$ is expected for all parameters with $m_{\tilde{t}_1} \lesssim 20\text{GeV}$ in the allowed range in Figs.1 and 8. Detail analyses with Monte Carlo studies including possible dominant background process $ep \rightarrow e\tilde{c}\tilde{c}X$ can be found in Ref.[30].

Besides the collider experiments we should concern the constraints on the model from non-accelerator experiments. The proton decay life time for the typical parameter sets are presented in Table.V, where we take the simplest SU(5) SUSY GUT model and only consider the decay mode $p \rightarrow K^+\nu_\mu$ [31]. In Table.VI we show the neutralino relic abundance $\Omega_{\tilde{Z}_1} h_0^2$ [32], where we take the lightest neutralino (LSP) as the pure photino because the photino component of LSP is larger than 98% in our parameter sets. From the Tables.V and VI, we find that all the parameter sets (A) \sim (D) are not excluded by the commonly accepted bounds $\tau_p \gtrsim 1 \times 10^{32}(\text{yr})$ and $0.1 \lesssim \Omega_{\tilde{Z}_1} h_0^2 < 1$. Note that they are not trivial results. It has been pointed out that the proton decay favors a large value of $\xi_0 \equiv m_\infty/M_\infty$ but the cosmology of neutralino dark matter disfavors large value of ξ_0 [33]. So our parameter sets satisfy automatically these two constraints simultaneously.

7 Conclusion

We have investigated the possibility for existence of the light stop $m_{\tilde{t}_1} = 15 \sim 16\text{GeV}$ and the neutralino $m_{\tilde{Z}_1} = 13 \sim 14\text{GeV}$ in the MSGUT scenario taking into account of the present experimental bounds on the SUSY parameter space. We have pointed out that the existence of such stop could change the dominant decay mode of some particles. For example, the stop modes $\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1^*\tilde{Z}_1$ and $h \rightarrow \tilde{t}_1\tilde{t}_1^*$ could dominate over respectively the conventional modes $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1$ and $h \rightarrow b\bar{b}$ even for relatively light gluino and Higgs. As a consequence, present experimental bounds on the their masses could be weakened, $m_{\tilde{g}} \gtrsim 85\text{GeV}$ and $m_h \gtrsim 55\text{GeV}$. Note that these bounds have been obtained by the parton-level Monte-Carlo calculation (no hadronization). In order to get correct lower bounds we should perform the exact Monte-Carlo including the detector efficiency. It seems that there is a finite parameter region allowing existence of such light stop even if we consider the present experimental data. Inversely, if such light stop was discovered at TRISTAN, masses and mixing parameters of the other SUSY partners as well as

masses of the Higgs and the top will be severely constrained, for example, $m_{\tilde{g}} \simeq 85\text{GeV}$, $m_{\tilde{W}_1} \lesssim 50\text{GeV}$, $110\text{GeV} \lesssim m_{\tilde{\ell}} \lesssim 140\text{GeV}$, $120\text{GeV} \lesssim m_{\tilde{q}} \lesssim 160\text{GeV}$, $\theta_t \simeq 0.9$, $m_h \lesssim 65\text{GeV}$ and $130\text{GeV} \lesssim m_t \lesssim 140\text{GeV}$. Actually, the light stop and its relatively light accompaniments, the gluino \tilde{g} , the light neutralinos $\tilde{Z}_{1,2}$, and the neutral Higgs h , should be visible near future at LEP, HERA and Tevatron.

We have exemplified that if we discover the light stop we will be able to constrain severely all the SUSY parameters at the unification scale. We can conclude that, therefore, the discovery of the stop will bring us a great physical impact. Not only it will be the first signature of the top flavor and the supersymmetry but also it could shed a light on the physics at the unification scale.

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Figure Captions

Figure 1: Excluded region in $(\theta_t, m_{\tilde{t}_1})$ plane by LEP with $\Delta\Gamma_Z < 28\text{MeV}$.

Figure 2: Contour of $m_{\tilde{Z}_1} = 13 \sim 14\text{GeV}$ in (μ, M_2) plane for $\tan\beta=2$. Excluded region by LEP is also depicted.

Figure 3: Allowed region in $(\mu, \tan\beta)$ plane for $M_2 = 24\text{GeV}$.

Figure 4: $m_{\tilde{g}}$ dependence of branching ratios of gluino. Sum over quark flavors $q, q' = u, d, c, s$ are taken. Input parameters are $\tan\beta = 2$, $\mu = -150\text{GeV}$, $m_{\tilde{t}_1} = 15\text{GeV}$, $\theta_t = 0.7$, $m_t = 135\text{GeV}$, $M_2 = 22\text{GeV}$ and $m_{\tilde{q}} = 2m_{\tilde{g}}$.

Figure 5: Expected number of events from $p\bar{p} \rightarrow \tilde{g}\tilde{g}X$ at CDF. Input parameters are $\tan\beta = 2$, $\mu = -150\text{GeV}$, $m_{\tilde{t}_1} = 15\text{GeV}$, $\theta_t = 0.9$, $m_t = 135\text{GeV}$, $M_2 = 22\text{GeV}$ and $m_{\tilde{q}} = 2m_{\tilde{g}}$.

Figure 6: Stop mass contours in $(\mu, \tan\beta)$ plane for fixed m_t . Each line corresponds to contour of $m_{\tilde{t}_1} = 16\text{GeV}$ for the fixed m_t value. We also plot the mass m_h contours as well as the LEP bounds.

Figure 7: Expected number of events from $Z \rightarrow hZ^*$ at LEP. Input parameters are $\tan\beta = 2$, $m_{\tilde{t}_1} = 16\text{GeV}$, $m_{\tilde{Z}_1} = 14\text{GeV}$ and $\alpha = -0.6$.

Figure 8: Allowed region $(\mu, \tan\beta)$ plane for $M_2 = 24\text{GeV}$. Points denoted by A, B, C and D are correspond to typical parameter sets in the text.

Table I Typical parameter sets

masses in GeV	A	B	C	D
M_2	24	24	24	24
$\tan \beta$	2.38	2.20	2.10	2.10
μ	-140	-140	-116.5	-170.7
m_t	140	137	130	141
M_∞	29.3	29.3	29.3	29.3
m_∞	126.2	118.3	101.0	130.5
A_∞	313.6	303.4	250.9	361.5
μ_∞	-122.2	-121.5	-98.6	-151.7
$m_{\tilde{t}_1}$	16.5	16.3	16.5	16.3
$m_{\tilde{t}_2}$	216.5	210.5	203.6	209.2
θ_t	0.896	0.893	0.867	0.931
$m_{\tilde{b}_1}$	116.6	111.5	106.3	111.3
$m_{\tilde{b}_2}$	149.0	142.4	128.4	152.6
$m_{\tilde{u}_L}$	141.9	135.4	120.8	146.4
$m_{\tilde{u}_R}$	144.5	137.9	123.5	148.6
$m_{\tilde{d}_L}$	156.9	150.1	136.5	159.6
$m_{\tilde{d}_R}$	148.9	142.2	128.1	152.5
$m_{\tilde{\ell}_L}$	134.0	126.2	109.9	137.5
$m_{\tilde{\ell}_R}$	131.9	124.1	107.4	135.6
$m_{\tilde{\nu}}$	116.1	108.3	89.7	122.0
m_h	63.4	59.0	55.1	56.2
m_A	197.3	194.4	162.8	232.4
m_H	210.4	208.9	181.0	245.0
m_{H^+}	212.9	210.2	181.4	245.8
α	-0.53	-0.56	-0.62	-0.54
$m_{\tilde{Z}_1}$	14.1	14.2	14.2	14.1
$m_{\tilde{Z}_2}$	47.3	49.2	51.5	48.1
$m_{\tilde{Z}_3}$	151.3	149.9	128.6	177.6
$m_{\tilde{Z}_4}$	176.7	177.3	158.4	203.9
$m_{\tilde{W}_1}$	45.1	46.6	49.6	45.1
$m_{\tilde{W}_2}$	175.9	175.5	156.5	201.2
$m_{\tilde{q}}$	85.9	85.9	85.9	85.9

Table II Branching ratios of top

	A	B	C	D
$t \rightarrow \tilde{t}_1 \tilde{Z}_1$	0.065	0.070	0.084	0.063
$t \rightarrow \tilde{t}_1 \tilde{Z}_2$	0.047	0.047	0.076	0.029
$t \rightarrow \tilde{t}_1 \tilde{g}$	0.399	0.389	0.330	0.437
$t \rightarrow bW^+$	0.489	0.494	0.510	0.471

Table III Branching ratios $Z \rightarrow \tilde{Z}_i \tilde{Z}_j [\times 10^{-5}]$

A	B	C	D
5.4	4.1	5.2	2.3

Table IV Branching ratios of gluino

	A	B	C	D
$\tilde{g} \rightarrow q\bar{q}\tilde{Z}_1$	0.236	0.261	0.337	0.220
$\tilde{g} \rightarrow q\bar{q}\tilde{Z}_2$	0.054	0.050	0.046	0.052
$\tilde{g} \rightarrow q\bar{q}'W_1$	0.166	0.161	0.153	0.163
$\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1^* \tilde{Z}_1$	0.544	0.528	0.464	0.565

Table V Proton decay life time $[\times 10^{32} \text{ yr}]$

A	B	C	D
2.9	2.7	1.9	3.6

Table VI Neutralino relic abundance ($\Omega_{\tilde{Z}_1} h_0^2$)

A	B	C	D
0.50	0.42	0.25	0.55

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